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A review of electrohydrodynamic enhancement of heat transfer

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Abstract

The heat transfer duty of heat exchangers can be improved by heat transfer enhancement techniques. In general, these techniques can be divided into two groups: active and passive techniques. The active techniques require external forces, e.g. electric field, acoustic or surface vibration etc. The passive techniques require fluid additives or special surface geometries. Electrohydrodynamic (EHD) techniques have been introduced as one of the types of active heat transfer enhancement techniques. This paper presents a review of research works on electrohydrodynamic heat transfer enhancement. This paper can be used as the first guideline for the researcher in using EHD techniques for heat transfer enhancement.

Keywords: Electrohydrodynamic; Condensation heat transfer; Boiling heat transfer; Heat transfer enhancement

Contents

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1. Introduction

Besides the improvement of the performance of the heat exchanger at the same heat transfer area, heat transfer enhancement enables a considerable decrease in the size of the heat exchanger at the same performance. In general, enhancement techniques can be divided into two groups: namely active and passive techniques. The active techniques require external forces, e.g. electric field, acoustic or surface vibration. The passive techniques require special surface geometries (such as rough surface, extended surface for liquids etc.) or fluid additives. Both techniques have been used by researchers for 140 years for increasing heat transfer rate in heat exchangers. Over the past 70 years, the heat transfer enhancement by using a strong electric field has been continuously studied. However, most of the early work concentrated on the enhancement of single-phase flow. In the last 30 years, many industrial and academic researchers have shown the greater potential of EHD in enhancing two-phase heat transfer. A large number of papers on the EHD enhancement of heat transfer have been published in open literature. Some papers have presented the review of these researches e.g. Allen and Karayiannis [1], Eames et al. [2]. However, the review of this research is not up-to-date.

The aim of this paper is to present a critical review of the work done on the effect of EHD on the single-phase, two-phase heat transfer and indicate the state of the art in this area, which is of importance for heat transfer enhancement research in the future.

2. General principle of the electrohydrodynamic enhancement of heat transfer

The electrohydrodynamic (EHD) enhancement of heat transfers refers to the coupling of an electric field with the fluid field in a dielectric fluid medium. In this technique, either a DC or an AC high-voltage low-current electric field is applied in the dielectric field medium flowing between a charged and a receiving (grounded) electrode [3].

The physical basis of the electrically enhanced condensation and boiling are due to the EHD force, (f_e), generated by an electric field and is given by Eq. (1) [4]:

$$f_e = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left\langle E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T \rho\right\rangle \quad (1)$$

Eq. (1) can be further written in a more detailed form for non-polar fluids [4] as follows:

$$f_e = f_1 + f_2 + f_3 + f_4 \quad (2)$$

Nomenclature

A	empirical constant
C_{pl}	specific heat of liquid (kJ/kg K)
E	applied voltage (V/m)
E_{max}	breakdown voltage (V/m)
f	empirical constant
h_{lg}	latent heat of vaporization (kJ/kg)
h_E	heat transfer coefficient under electric field (W/m^2 K)
k_1	thermal conductivity (W/m K)
l	inter-electrode gap (m)
m	empirical constant
n1	empirical constant
q	electric field space charge density(C/m^3)
T	temperature, (°C)
ΔT	temperature difference (K)
V	dimensionless group
ε	electric permittivity of the fluid, $\varepsilon = \varepsilon_0 \kappa$ (F/m)
ε_0	electric permittivity of free space (F/m)
κ	relative permittivity, dielectric constant
ρ	density (kg/m^3)
λ^*	the most unstable wavelength in the presence of the electric field (m)

$$f_e = qE - \frac{1}{2}E^2(\nabla\varepsilon) + \frac{1}{6}\varepsilon_0(k-1)(k+2)(\nabla E)^2 + \frac{1}{6}\varepsilon_o E^2 \nabla\langle(k-1)(k+2)\rangle \quad (3)$$

where ε is the electric permittivity of the fluid (F/m),ε_0 is the electric permittivity of vacuum (8.854×10^{-12} F/m), k is the relative permittivity ($\varepsilon/\varepsilon_0$), ρ is the density (kg/m^3), q is the electric charge density (C/m^3), and E is the applied electric field strength (V/m).

The first term on the right of Eq. (3), known as the electrophoretic force, is the Coulomb force acting on the free charges in a fluid. An electrophoretic force exists once a net charge is created in the fluid and it becomes dominant in applications. The electric field induces a fluid motion called "corona wind". The effect of the Coulomb force is presented by Stuetzer's experiment as shown in Fig. 1.

The second term (f_2) is a consequence of inhomogeneity or spatial change in the permittivity of the dielectric fluid due to non-uniform electric fields, temperature gradients, and phase differences. As shown in Fig. 2, the two media have dielectric constants κ_1 and κ_2 and equivalent resistivities ε_1 and ε_2.

The third term (f_3) comprises the dielectophoretic and electrostrictive forces, within the fluid. Dielectophoretic force presents the non-uniformity of the electric field (Fig. 3). Condensate is pushed by this force into a higher electric field strength.

The fourth term (f_4) is the electrostriction force. This force depends on non-uniformity of electric permittivity. A similar principle applies when a charged needle electrode is brought close to a liquid surface. The liquid surface extends into the gas toward the electrode as shown in Fig. 4. This phenomenon is called the liquid-extraction phenomena. This occurs again due to the EHD-induced surface instability on the gas-liquid interface.

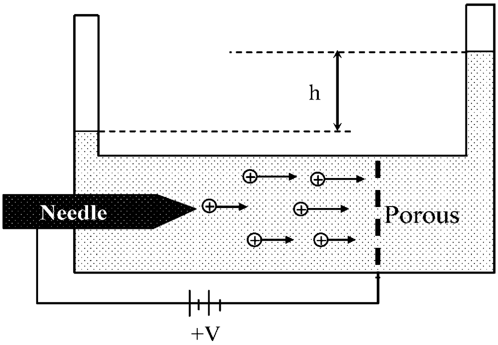


Fig. 1. Schematic diagram of Stuetzer's experiment [5].

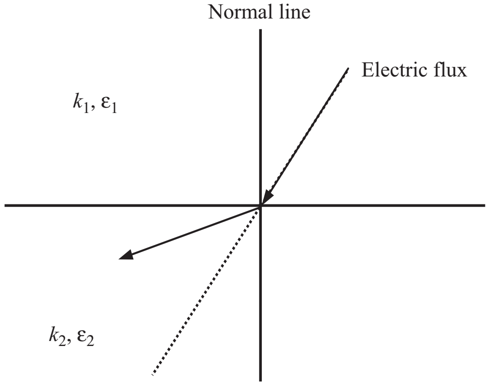


Fig. 2. Refraction of electric flux for $\varepsilon_1 > \varepsilon_2$.

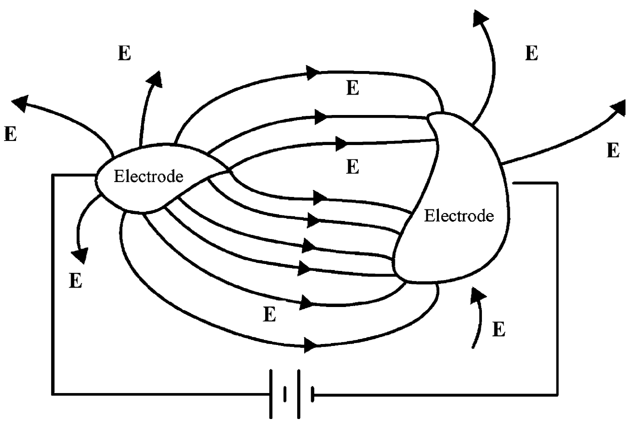


Fig. 3. Uniformity of the electric field distribution.

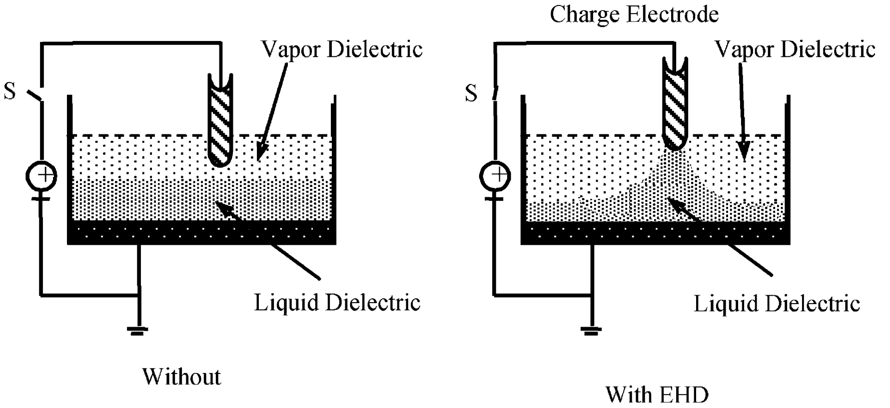


Fig. 4. Liquid-extraction phenomenon [3].

3. EHD in single phase heat transfer

3.1. On horizontal surfaces

As smaller and more effective thermal systems are needed, the improvement of the heat or mass transfer has been carried out more than 140 years ago. The enhancement of single-phase heat transfer processes, especially in gas systems, is an area where scientists and engineers have spent a great deal of effort. There are a number of papers on the EHD enhancement of heat transfer. Fernandez et al. [6] presented experimental results of an electrohydrodynamically-enhanced oil heater of annular cross-section. The results showed that when a high DC voltage of 30 kV was applied across the annular gap, the radial motion of the fluid was strongly induced. This resulted in an increase of heat transfer rate of more than 20 fold over the fully developed laminar flow, yet the pressure drop only increased three fold. Kui [7] studied the effect of an electric field on the heat transfer of air to air in a heat pipe heat exchanger. A correlation in terms of heat transfer coefficient, heat transfer rate, and temperature efficiency, was proposed as a function of the Reynolds number, the voltage supplied and its pattern (static and impulse).

Moatimid [8] studied electrohydrodynamic stability with heat and mass transfer of two fluids with a cylindrical interface. The effect of a tangential periodic electric field on the stability of a cylindrical interface between two liquid phases of fluid was considered. The two phases were enclosed between two cylindrical surfaces coaxial with the interface admitting heat and mass transfer. A general dispersion equation was derived and discussed. The analytical results were confirmed numerically. Later, Moatimid [9] showed the linear stability of an interface between two dielectric viscous fluids separated by a horizontal interface. The system was stressed by a periodic electric field in a direction perpendicular to the interface. The analysis was based on the multiples time scale technique [10]. The effect of surface tension, low viscosity, velocity streaming and gravity on the critical surface charge density and on the electric field were discussed. The analytical results were confirmed by comparing them with numerical results.

In 1995, Owsenek et al. [11] experimentally investigated the corona wind enhancement of free convection using a heated horizontal flat plate. High-voltage was supplied to a needle

suspended above a heated plate. The increased plate surface temperature was measured by an infrared camera for calculating the heat transfer coefficients. Paschkewitz and Pratt [12] investigated the effect of fluid properties on the heat transfer enhancement by EHD technique. Heat transfer rate, pressure drop, electrical power requirements, and the transition between the viscous-dominated and electrically-dominated flow regimes, were investigated. Three cooling oils having widely varying physical properties were used as working fluids. It was found that the EHD had significant effect in lower viscosity liquids at the same low Reynolds number. The theoretical results were verified by comparing them with available experimental and analytical results.

Wangnipparnto et al. [13] studied the air-side performance of a thermosyphon heat exchanger in the low Reynolds number region with and without the presence of the EHD. For the test results without EHD, the results obtained from Zukauskas's correlation under-predict the measured data. For the test results with EHD, when a voltage lower than 15.5 kV, was applied the heat transfer coefficient slightly increased. The results from a flow visualization study showed that the corona wind was the major mechanism of the heat transfer enhancement. However, for the larger Reynolds number region, the corona wind may be opposite to the airflow direction. The effect of EHD decreased as the Reynolds number increased. Based on the experimental data of Wangnipparnto et al. [13], a correlation was proposed:

$$\frac{Nu_{\mathrm{EHD}}}{Nu_{\mathrm{NON_EHD}}} = 1 + 1.21\mathrm{Re}_{\mathrm{D}}^{-0.48}\left(\frac{E}{E_{\max}}\right)^{\left(1.024/\mathrm{Re}_{\mathrm{D}}^{-0.62}\right)} \tag{4}$$

For $58 < \mathrm{Re_D} < 230$ and $15.5kV < E < E_{\max}$

In their second paper, Wangnipparnto et al. [14] applied a numerical method to analyze the balanced and unbalanced thermosyphon heat exchangers with and without the presence of the EHD. The calculated heat transfer rate for water and R-134a in the balanced thermosyphon heat exchanger was in good agreement with measured data. The measured data were fitted to obtain the following correlation.

$$\frac{Nu_{\mathrm{EHD}}}{Nu_{\mathrm{NON_EHD}}} = 1 + 1.33\mathrm{Re}_{\mathrm{D}}^{-0.50976}\left(\frac{E}{E_{\max}}\right)^{\left(3.126/\mathrm{Re}_{\mathrm{D}}^{-0.3292}\right)} \tag{5}$$

where

$$Nu_{\mathrm{NON_EHD}} = 0.146\mathrm{Re}^{0.9077}\mathrm{Pr}^{0.36} \tag{6}$$

where $E/E_{\max}$ is the applied voltage ratio, and $E_{\max}$ is the breakdown voltage.

Kasayapanand and Kiatsiriroat [15] numerically investigated the heat transfer enhancement with electrohydrodynamic technique using different wire electrode arrangements in lamina forced convection inside a wavy channel. Air was used as working fluid. Electrodes charged with DC high-voltage generated the electric field. The interactions among electric, flow field, and temperature field were inducted in the mathematical modeling. The simulation was firstly conducted with experimental data in case of rectangular flat channel and the results were in good agreement with experimental data. The results were found that the heat transfer coefficient with the presence of electric field increased with decreasing the Reynolds number and distance between the wire electrodes and the wall surface are augmented. The heat transfer enhancement was also dependent on

the number of the wire electrodes, the number of wave per length, and the wave aspect ratio.

Seyed-Yagoobi [16] studied the three types of EHD pumping mechanisms (charge injection, induction and dissociation). Both single-phase liquid and two-phase liquid/vapor were investigated. EHD conduction pumping and induction pumping, in contrast, both show a great promise for pumping of single-phase liquid and liquid films, in small and large scales, often present in varies phase change devices.

4. EHD in two-phase heat transfer

4.1. EHD in condensation heat transfer

The phase change occurring during boiling and condensation is a very important mode of heat transfer. Therefore, there is further need to improve the methods of heat transfer enhancement in both evaporators and condensers. The study of the effects of EHD on condensation began 30 years ago. The physical mechanisms appearing during the application of EHD to condensation heat transfer enhancement are as follows [2]:

- thinning of the condensate film by stripping the liquid from the condensation surface [17,18]
- the change of film condensation to pseudo-dropwise condensation [17–19]
- dispersion of the condensate using electrostatic atomization [17]
- disturbing the accumulation of non-condensable gases at the liquid-vapour interface [20]
- inducing perturbations and waviness into the condensate film [21–23]

4.1.1. EHD in condensation heat transfer on horizontal surfaces

There have been a number of experimental studies concerning EHD in condensation heat transfer on a horizontal surface. Holmes et al. [24] experimentally examined the effect of a non-uniform, alternating, 60-cycle, electric field on the condensation heat transfer of Freon-114. The condensing surface was a grounded cooled flat plate. A voltage ranging between 0 and 60 kV was applied to a second plate placed above the first one. The non-uniform electric field was produced by varying the angle between both plates. The measured heat transfer was compared with the analytical results. For voltages less than 40 kV, reasonable agreement was obtained between the experimental data and predicted results. However, the results were unpredictable at voltages over 40 kV. The heat transfer coefficients in the presence of the electric field were ten times higher than those without an electric field. Trommelmans et al. [25] experimentally and theoretically studied the condensation heat transfer coefficient on the underside of a horizontal plate with and without a uniform electric field. The electric field was applied perpendicular to the plate. R-11, R-113, and R-114 were used as working fluids. A correlation was proposed to describe the influence of the electric field upon the film coefficients by means of the most-unstable wavelength which could be produced by using a stability analysis assuming a sinusoidal perturbation of the vapor-liquid interface and through a dispersion relation that interrelates the length and the frequency of the disturbance [26]. In their second paper,

Trommelmans and Berghanans [27] extended the theoretical model to analyze the film condensation outside horizontal tubes. They found that the actual form of the interface should be included in the mathematical model.

Bologa et al. [28] experimentally and theoretically investigated the influence of the physical mechanisms of electric field on the condensation heat and mass transfer processes. The heat removal and inter-phase heat transfer in vapor and gas–liquid dispersed systems were discussed. Based on the experimental data, correlations were proposed for predicting the heat transfer coefficient. Jia-Xiang et al. [29] studied the EHD coupled heat transfer systems using a double electrode cylinder heat transfer model. Freon-11 was used as the working fluid. The condensation heat transfer coefficient, the boiling heat flux and the saturation pressure were measured. The results showed that the electrical field had a significant effect on both boiling and condensation heat transfer.

Singh et al. [3] investigated the applicability of the EHD techniques for tube side condensation heat transfer enhancement. The test section consisted of a horizontal double tube heat exchanger with refrigerant R-134a flowing in the inner tube and water flowing in the outer tube. Two different configurations of tubes, smooth and micro-fin copper tubes were tested. The dimensions of the inner tube were 12.7 mm outside diameter and 305 mm long. Six different electrodes of various diameters and spacing, were tested. The results showed that the EHD introduced an additional penalty of the pressure drop of 1200, 12.35 and 3.36 times higher than those without electrode for stratified flow, wavy flow and wavy-annular flow, respectively.

Cheung et al. [30] studied the EHD-assisted external condensation of R-134a on smooth horizontal and vertical tubes using R-134a as the working fluid. The effects of heat flux, electrode gaps and applied electric field potential were conducted and discussed. It was concluded that the effective removal of the condensate through EHD-induced liquid extraction and dispersion phenomena were the mechanism of heat transfer enhancement. Silva et al. [31] presented work on the EHD enhancement of external condensation of refrigerant R-134a on horizontal single enhanced tubes. Experiments were performed on two types of commercial enhanced tubes. The tests were conducted at the EHD voltage ranging between 0 and 25 kV, saturation temperature ranging between 10 and 40 °C, and heat flux ranging between 10 to 40 kW/(m^{2}K). The result showed that the designed electrode worked well on enhanced tubes, and was able to substantially improve the external condensation heat transfer coefficient.

Al-Ahmadi et al. [26] proposed a new set of correlations for evaluating the heat transfer coefficient of EHD assisted condensation heat transfer on outside and inside horizontal smooth tubes. The test runs were done on various refrigerants and electrode systems. The following correlations were developed from a wide range of measured data.

$$\frac{h_E \lambda^*}{k_l} = Nu_E = A\left[\frac{V^m h'_{lg}\left(\frac{\lambda^*}{l}\right)^f}{C_{pl}\Delta T}\right]^{n1} \tag{7}$$

where

$$h'_{lg} = h_{lg} + 0.86 C_{pl} \Delta T \tag{8}$$

where h_E is the heat transfer coefficient in the presence of the electric field (W/m^{2}K), λ^* is the most unstable wavelength in the presence of the electric field (m), k_l is the thermal conductivity (W/m K), V is the dimensionless group, C_{pl} is the specific heat of liquid

(kJ/kg K), ΔT is the temperature difference (K), h_{lg} is the latent heat of vaporization (kJ/kg), l is the inter-electrode gap, and A, m, f, nl are empirical constants.

Butrymowicz et al. [4] investigated the enhancement of condensation heat transfer of a horizontal finned tube with rod and mesh electrodes placed beneath the tube. The HCF-123 was used as a working fluid. As expected, the application of EHD for the new tube-electrode configuration increased the heat transfer coefficient (from 27 to 110%), depending on the electrode potential. In their second paper, Butrymowicz et al. [32] presented a short state-of-the-art review on the passive and active enhancement of condensation heat transfer techniques. Particular attention was paid to methods concerning the augmentation of the condensate drainage. The method of condensate drainage enhancement by using a drainage strip was presented and a novel EHD technique was presented. For both methods, they provided their own experimental results and theoretical models.

Compared to the experimental studies, a few works have reported on the theoretical study of two-phase heat transfer. Yu et al. [33] developed an experimental model to verify the calculation of temperature control of EHD micro heat pipes. The electric field intensity, set-point temperature and gap between the upper and lower set-point temperatures were found to have a significant effect on temperature control. Later, Cotton et al. [34] numerically investigated the effect of electric field distributions in electrohydrodynamic two-phase flow regimes.

Cao et al. [35] investigated the drying characteristics of wheat treated by a high-voltage electrostatic field (HVEF). The drying rate of wheat in a HVEF was significantly higher than that of a control for various drying temperatures and electric field strengths. A Multiple points-to-plate corona discharge electrode of HVEF improved the average drying rate by 2.1, 2.0 and 1.7 respectively for 10, 7.5 and 5 kV/cm. The drying rate tended to increase with increasing the voltage and increased with decreasing the discharge gap. The power consumption was negligible with the current of a few microamperes.

Lin and Jang [36] numerically investigated a 3D numerical thermal-hydralic analysis for a micro-channel flow induced by an electrohydrodynamic pump. In this study, the different electrode pitches (5–200 μm), electrode angles (2-6°) and different applied voltage (100–500 V) were investigated. HFE-7100 and oil were used as working fluid. It was found that the channel pitch decreased or the applied voltage increased with increasing the pressure head, flow rate and wall cooling capacity.

4.1.2. EHD in condensation heat transfer on vertical surfaces

As for the condensation heat transfer on a horizontal surface, EHD in condensation heat transfer on a vertical surface has been studied by many researchers, for example, Velkoff and Miller [37] improved the condensation heat transfer of Freon-113 in a vertical copper tube by using electrostatic fields. The results indicated that the increases in heat transfer of 150% could be obtained by using screen electrodes placed parallel to the cooled copper plate. These results were controllable and readily reproducible. Choi and Reynolds [38] proposed a correlation in terms of the most-unstable wavelength of the perturbed condensate film for condensation heat transfer inside vertical tubes. Later, Choi [39] studied the effect of an electric field on the condensation heat transfer of Freon-113 inside a vertical tube. The condensate interface was stressed by a radial DC field. The results showed that the electric field had a significant effect on the increase of the condensation

heat transfer coefficient. The increase was related to the instability waves at the liquid film interface. The proposed correlation was presented in terms of a modified Nusselt number and Reyleigh numbers. The characteristic length was the most unstable wavelength in the system, and the driving force acting on the film was an equivalent electrohydrodynamic force.

Bologa and Didkovesky [40] conducted experiments to study the effect of an electric field on the film condensation heat transfer enhancement on a vertical flat plate and tube. The strength, frequency and uniformity of the electric field were varied. *n*-hezane, R-113 and diethyl ether were used as working fluids. The correlation for the heat transfer coefficient was proposed based on their experimental data. In their second paper, Bologa et al. [41] presented experimental results of heat transfer in film vapour condensation from a vapour-gas mixture on a vertical plate under the influence of an electric field. They discussed the effects of the gas concentration in the vapour, medium pressure, temperature difference between the vapour-gas mixture and the wall, difference of potentials, electric current strength, physical properties of the liquid phase and of the vapour-gas mixture on the degree of heat transfer enhancement. Later, Bologa et al. [42] presented experimental results on the enhancement of condensation heat transfer by an electric field. The state of equilibrium of a two-phase system for various shapes of interface and the role of capillary processes were studied. The results showed that the condensation heat transfer enhancement in an electric field was caused by interface deformation and by the associated effect of phase equilibrium displacement.

Smirnov and Lunev [43] experimentally and theoretically studied the enhancement condensation of heat transfer of non-polar fluid (R-113) and weakly polar fluid (diethyl ether) on a vertical tube using DC and AC electric fileds. A correlation baesd on their data for predicting the heat transfer coefficient was presented. Didkovsky et al. [44] presented experimental results of heat transfer and hydrodynamics for film condensation of a stagnant pure vapour on vertical short surfaces in electric fields of different strength, frequency and uniformity. With negligible power expenditure on setting up the electrostatic field, a 20-fold increase in the heat transfer coefficient, was attained. Under the electrohydrodynamic effect, due to reduction of the film thickness caused by spraying of condensate into the vapor phase and by formation of transverse waves, the heat transfer tended to increase. Dyakowski et al. [45] theoretically investigated the condensate film outside vertical plates subjected to gravitational and EHD forces. The correlation for heat transfer coefficient as a function of film thickness ratio and of the most unstable wavelength was given.

In 1996, Wawzyniak and Seyed-Yagoobi [46] studied the heat transfer enhancement of the EHD-extraction phenomenon. A smooth and an enhanced tube were used for test sections and refrigerant-113 was used as the working fluid. A 50 kV, 5 mA DC power supply was used to generate the required electric potential. Cheung et al. [30] conducted an experiment to study the potential of heat transfer enhancement by EHD technique on the external condensation of R-134a in a vertical tube. Experimental results showed a potential in utilizing EHD to enhance heat transfer during condensation. Due to the effective removal of the condensate through EHD-induced liquid extraction and dispersion phenomena, the heat transfer was enhanced. Al-Ahmadi et al. [26] proposed a new set of correlations for estimating the heat transfer coefficient of condensation heat transfer using EHD on outside and inside vertical smooth tubes. The test runs were done with varies electrode systems and various refrigerants.

Table 1
List of the EHD enhancement of condensation

Source	Working fluid	h_{EHD}/h_o (max)
Bologa and DidKovsky [47]	Diethyl ether	20
	R-113, hexane	10
	Diethyl ether	20
Bologa et al. [41]	Hexane–carbon dioxide	5
Bologa et al. [28]	Freon-113	~20
Bologa et al. [20]	R-113–helium	1.8
	R-113–air	2.6
	R-113–carbon dioxide	3.0
	Hexane–air	5.0
Butrymowicz et al. [4]	R-123	~2
Cheung et al. [30]	R-134a	7.2
Choi [39]	Freon-113	~2
Choi and Reynold [38]	R-113	2
Cooper and Allen [48]	R-12 and R-114	2.9
Damianidis et al. [49]	R-114	1.08
Didkovsky and Bologa [44]	non-polar and polar dielectrics	20
Holmes and Chapman [24]	R-114	Up to 10 times
Jia-Xiang et al. [29]	Freon-11	~1.85
Seth and Lee [50]	R-113	1.6
Silva et al. [31]	R-134a	~3
Singh et al. [3]	R-134a	6.5
Smirnov and Lunev [43]	R-113, diethylether	3.6
Sunada et al. [19]	R-123	~6
Trommelmans and Berghmans [27]	R-11, R-13 and R-114	1.1
Velkoff and Miller [37]	Freon-113	1.5
Wawzyniak and Seyed-Yagoobi [46]	R-113	6.1
Yabe et al. [51]	Water, R-113	2.24
Yabe et al. [52]	Silicone oil, R-113	4.5
Yamashita et al. [18]	C_6F_{14} (perfluorohexane)	6
	R-114	6
	n-perfluorohexane	4

Table 1 briefs the degrees of condensation heat transfer enhancement accomplished with EHD reported by various researchers.

4.2. EHD in boiling heat transfer

Compared to EHD in two-phase condensation heat transfer characteristics, EHD in two-phase boiling heat transfer is more complex. Because nucleate boiling dominates the heat-transfer process in the evaporators of vapour-compression refrigeration systems, therefore it can be clearly seen from the literature that the effects of the EHD enhancement on the boiling process have been more extensively studied than on the condensation process. The mechanisms by which EHD techniques enhance boiling process are summarized as follow [2]:

- movement of vapour bubbles on the heated surface due to Maxwell stress [2,53,54]
- spreading of the vapour bubble base over the heat transfer surface [2,53,55]

- increasing the number of bubbles by breaking up large bubbles, there by decreasing the bubble detachment diameter and creating more turbulence [2,53,56]
- elimination of boiling hysteresis, thereby decreasing the degree of the superheat required to start nucleate boiling [1,2,56–59]
- improving the transitional and minimum film boiling conditions by destabilizing the blanketing vapour film [1,2,59]
- improving the wetting of the heating surface due to the decrease of surface tension
- [2,60,61]
- introducing the waves and perturbations at the surface of a boiling liquid, due to the instability of the vapour/liquid interface [2,62–64]

4.2.1. EHD in boiling heat transfer on horizontal surfaces

The effect of electrostatic fields on the maximum heat flux pool boiling on a large horizontal cylindrical heater was theoretically studied by Berghmans [65]. Comparison between the results obtained from the prediction and those obtained from the experiment was in good agreement. Allen and Cooper [57] demonstrated the application of an 8 kV electric field to a boiling of R-114. Ogata and Yabe [53] investigated the boiling of R-11 and a mixture of R-11 (98 wt %) and ethanal (2 wt %) in a pool over a horizontal copper tube. A positively charged mesh electrode, around and along an earthed copper tube were used. In their second paper, Ogata and Yabe [54] studied the boiling curves obtained from different enhanced and smooth surface geometries under various degree of EHD.

Papar et al. [66] studied the effect of various geometries of three different electrodes on pool boiling of a R-123/oil mixture over a horizontal smooth tube. The results showed that mesh electrodes yielded better results than helical wire or straight wire electrodes. Oh and Kwak [67] experimentally investigated the effect of a direct current electric field on nucleate boiling heat transfer in a single-tube shell/tube heat exchanger. R-11 and R-113 were used as working fluids and the water heating method was employed. Neve and Yan [68] studied the enhancement of heat exchanger performance by using combined electrohydrodynamics and passive methods. R-114 was used as working fluid. The results were compared with those from previous published work. It was found that the heat transfer rate increased due to the enhanced nucleation rate and decreased critical bubble radius under a local electric field gradient. Computational analysis revealed that the shapes of passive enhanced surfaces created considerable increasing in the local field gradient to produce favourable conditions.

The behaviors of a bubble attached to a wall in a uniform electric field were numerically and experimentally investigated by Cho et al. [69]. Based on a finite-difference method, the orthogonal curvilinear coordinate system, generated numerically, was employed for the numerical solution. An air bubble attached to one plate of a parallel-plate electrode system under an applied electric field was studied. The numerical and experimental results showed good agreement. In their second paper, Cho et al. [70] numerically investigated the effects of a non-uniform electric field on the behavior of a bubble attached to a tip. The free boundary problem, which consists of the governing equation of an electric field and the normal stress at the bubble surface, was solved by using a generated composite orthogonal coordinate system to determine the equilibrium bubble shape.

Cheung et al. [71] optimized the electrode heat transfer surface geometry and also carried out flow visualization studies, which provided improved understanding of the

EHD-enhanced pool boiling heat transfer coefficients in a tube bundle. In this area of study, Verplaetsen et al. [72] considered the influence of an electric field on the heat transfer rate during pool boiling or film boiling of stagnant fluids on a horizontal surface. Knowledge of the equilibrium shape of the liquid–vapour interface was required for developing the method. The equilibrium shape was calculated using an iterative solution technique. A fourth order Runge-Kutta technique was applied to calculate the shape of the interface. A boundary element method was applied to determine the electric field. The results showed that the formed vapour bubbles became elongated under an electric field. This effect was included in the existing heat transfer models in order to estimate the effect of the electric field on the heat transfer coefficient of film boiling process.

Kweon et al. [73] experimentally studied the effects of DC/AC electric fields on the deformation and departure of a bubble attached to a wall. Three difference types of electrodes applied with non-uniformity of the electric field were used to examine the bubble behavior. The results showed that the departure process under AC electric field was associated with the bubble oscillation. This oscillation was composed of three different regions. It was found that the volume of the bubble departure dropped suddenly near the critical voltage and the reduction of this departure volume by the AC electric field was more effective than in the DC electric field. In their next paper, Kweon et al. [74] investigated the dynamic of bubble and the potential of an electric field on the enhancement of the nucleate boiling heat transfer. Experiments were performed under saturated pool boiling by using R-113 as working fluid. A plate-wire electrode was used to reform a steep electric field gradient around the wire. It was also found that, the strength and non-uniformity of the electric field had a significant effect on the boiling parameter and the latent heat transported by bubbles nearly corresponded to the total heat flux at high-voltage.

Karayiannis [75] presented the experimental results of electrohydrodynamic boiling heat transfer enhancement of R-123 and R-11 on the shell side of a smooth five-tube shell and tube heat exchanger by using a high intensity DC electric field. The tubes arranged in three rows were electrically heated. The electrode carrying the high voltage was fabricated from fourteen mild steel rods placed in between and around the tubes. The test was done at a heat flux ranging between 20 and $5\,kW/m^2$, and applied voltages ranging between 0 and 25 kV. The effect of pressure on the heat transfer enhancement was discussed.

Pascual et al. [76] presented an empirical correlation for electrohydrodynamic enhancement of free convection from heated horizontal cylinders. The proposed correlation was based on data from two different experiments. The first set of experiments involved free convection at a thin platinum wire dipped in R-123 under an applied uniform electric field. The second one involved free convection at a flooded tube dipped in R-123 with a non-uniform electric field. The heat transfer enhancement or the Nusselt number enhancement, ΔNu, due to the electric field was determined from the measured data. The enhancement correlation was proposed in terms of a "corrected electrical Rayleigh number", Ra_E, which accounted for the effect of a non-uniform electric field. The correlation was applicable over a range of Rayleigh numbers from 4.0×10^3 to 8.0×10^8. In their second paper, Pascual et al. [77] quantified the effect of electric forces on bubble dynamic in saturated nucleate boiling experiments of R-123. The experiment was conducted by using a 0.13 mm diameter platinum wire under an applied uniform electric field. The average number density of active nucleation sites, the average bubble departure frequency per nucleation site, and the frequency distribution of bubble departure diameters

were recorded by high-speed camera. Due to reductions in the number of active nucleation sites and the average bubble departure diameter, the presence of the electric field increased the natural convection contribution to the total heat flux, while the contribution of latent heat transport to the total heat flux were reduced. Later, Pascual et al. [78] studied bubble dynamics in saturated pool boiling of R-123 using a flat uniformly heated transparent surface with and without an applied electric field. For a specific heat flux, the use of the electric field reduced the surface temperature. This resulted in the suppression of the boiling and reduction of the latent heat contribution.

Feng et al. [79] used linear stability analysis to investigate the flow regimes associated with a horizontal internal two-phase gas–liquid flow in the presence and absence of an electric field. The momentum interchange between the two phases due to the entrainment was included in their analysis. The results showed that the application of the electric field promoted instability by providing the electrohydrodynamic extraction force.

4.2.2. EHD in boiling heat transfer on vertical surfaces

The Work by Yamashita et al. [80] was only one found in the literature concerning the electrohydronamic in boiling heat transfer on vertical surfaces. They experimentally studied the electrohydrodynamic enhancement of vertical falling film evaporation heat transfer of R-123 and its long-term effect on heat exchangers. The electrodes used for

Table 2
List of the EHD enhancement of boiling

Source	Working fluid	h_{EHD}/h_0(max)
Allen and Cooper [57]	R-114	up to 60
Blachowicz et al. [82]	Benzene	2
Bochirol et al. [83]	Tricholethylene and ethyl ether	2.7
	Methyl alcohol	6
Cheung et al. [71]	R-134a	5.1
Cooper [84]	R-114 + oil	13
Damianidis et al [56]	R-114 (smooth tube)	~1
	R-114 (low-fin tubes)	2.5
Feng and Seyed-Yagoobi [79]	R-134a	~4.5
Kawahira et al. [85]	R-11	4
Karayiannis [75]	R-123 and R-11	9.3
Karayiannis et al. [86]	R-114	4
Liu et al. [81]	R-123	2.1
Neve and Yan [68]	R-114	3
Ohadi et al. [87]	R-123	5.5
	R-11	1.7
Ogata et al. [88]	R-123	7
Papar et al. [66]	R-123	6
Schnurmann and Lardge [89]	*n*-heptane	~7
	20% solution of isopropyl alcohol in *n*-heptane	~7
	Perfluoromethylcyclohexane	~2
Watson [90]	*n*-hexane	2.6
Source	R-123 + R-134a	3
Yabe et al [91]	R-123	6
Yamashita and Yabe [80]	Acetone, benzene	1.82
Zheltukhin et al. [92]	*n*-diethyl ether	(acetone)

electrohydrodynamic enhancement utilized the following two electrohydrodynamic phenomenon: surface granulation by a nearly uniform electric field and extracting the liquid by a non-uniform electric field.

Liu et al. [81] experimentally studied the effect of the electrode polarity on EHD enhancement of boiling heat transfer in a vertical tube using R-123 as working fluid. Either positive or negative high-voltage was applied to the cylindrical brass as the electrode. The stainless steel tube was a ground. It was found that the positive high-voltage gave much greater enhancements and requires lower average electric field strength to obtain a maximum enhancement factor than the negative high voltage. At heat flux of 1.5 kW/m^2 with average electric field strength of 1333 kV/m obtained the maximum enhancement factor of 2.1 for the positive polarity. The breakdown strength of positive polarity was slightly lower that of negative polarity.

Table 2 shows that the EHD enhancements of boiling are reported by various researchers.

5. Conclusions

In this study, the effects of electrohydrodynamics on heat transfer characteristics can be divided into two groups according to the mechanism of heat transfer. The effect of EHD on single-phase heat transfer characteristics on a horizontal surface has been studied by a number of researchers. However, no paper has presented studies for a vertical surface. For condensation heat transfer, the review indicates that numerous works have reported the heat transfer characteristics for both vertical and horizontal surfaces. For boiling heat transfer, although many papers have been published, only two of these papers presented the effect of electrohydrodynamics on heat transfer characteristics on vertical surfaces. The study points out that although numerous EHD studies have been conducted on the single-phase and two-phase heat transfer, the study on some heat transfer mechanisms is limited, especially on the single phase heat transfer characteristics and boiling heat transfer characteristics on a vertical surface.

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References

[1] Allen PHG, Karayiannis TG. Electrohydrodynamic enhancement of heat transfer and fluid flow. Heat Recov Syst CHP 1995;15:389–423.
[2] Eames W, Sabir HM. Potential benefits of electrohydrodynamic enhancement of two-phase heat transfer in the design of refrigeration systems. Appl Therm Eng 1997;17:79–92.
[3] Singh A, Ohadi MM, Dessiatoun S. EHD enhancement of in-tube condensation heat transfer of alternate refrigerant R-134a in smooth and microfin tubes. ASHRAE Trans Symp 1997:813–23.
[4] Butrymowicz D, Trela M, Karwacki J. Enhancement of condensation heat transfer by means of EHD condense drainage. Int J Ther Sci 2002;41:646–57.
[5] Attwood SS, Stephen S. Electric and magnetic fields. New York: Dover Publications; 1967.

[6] Fernández J, Poulter R. Radial mass flow in electrohydrodynamically-enhanced forced heat transfer in tubes. Int J Heat and Mass Transfer 1987;30:2125–36.
[7] Kui L. The enhancing heat transfer of heat pipe by the electric field. Proceeding of Seventh International Heat Pipe Conference. USA: Begell House; 1993. p. 563–7.
[8] Moatimid GM. Electrohydrodynamic stability with mass and heat transfer of two fluids with a cylindrical interface. Int J Eng Sci 1994;33.
[9] Moatimid GM. Electrohydrodynamic instability of two superposed viscous miscible streaming fluids. Chaos Soliton Fract 2001;12:1239–57.
[10] Nayfeh AH, Balachandran B. Applied nonlinear mechanics. New York: Wiley; 1995.
[11] Owsenek BL, Seyed-Yagoohi J, Page RH. Experimental investigation of corona wind heat transfer enhancement with a heated horizontal flat plate. J Heat Transfer 1995;117:309–15.
[12] Paschkewitz JS, Pratt DM. The influence of fluid properties on electrohydrodynamic heat transfer enhancement in liquids under viscous and electrically dominated flow conditions. Exp Therm Fluid Sci 2000;21:187–97.
[13] Wangnipparnto S, Tiansuwan J, Jiracheewanun, Kiatsiriroat T, Wang CC. Air side performance of thermosyphon heat exchanger in low Reynolds number region: with and without electric field. Energ Convers Manage 2002;43:1791–800.
[14] Wangnipparnto S, Tiansuwan J, Kiatsiriroat T, Wang CC. Performance analysis of thermosyphon heat exchanger under electric field. Energ Convers Manage 2003;44:1163–75.
[15] Kasayapanand N, Kiatsiriroat T. EHD enhanced heat transfer in wavy channel. vol. 32 2005 p. 809–21.
[16] Seyed-Yagoobi J. Electrohydrodynamic pumping of dielectric liquids. J Electrostat 2005;63:861–9.
[17] Yabe A. Active heat transfer enhancement by appling electric fields. Proc ASME/JSME Therm Eng 1991;3:15–23.
[18] Yamashita K, Kumagai M, Sekita S, Yabe A, Taketani T, Kikuchi K. Heat transfer characteristics on an EHD condenser. Proc. ASME/JSME Thermal Eng. 1991;3:61–7.
[19] Sunada K, Yabe A, Taketani T, Yoshizawa Y. Experimental study of EHD pseudo-dropwise condensation. Proc ASME/JSME Therm Eng 1991;3:61–7.
[20] Bologa MK, Savin IK, Didkovsky AB. Electric-field-induced enhancement of vapour condensation heat transfer in the presence of a non-condensable gas. Int J Heat Mass Transfer 1987;30:1558–77.
[21] Budov VM, Kir'yanov BV, Shemagin IA. Heat transfer in the laminar-wave section of condensation of a stationary vapour. J Eng Phys 1987;52(6):647–8.
[22] Grigor'eva NI, Nakoryakov VE. Exact solution of combined heat and mass transfer during film absorption. J Eng Phys 1997;33(5):893–8.
[23] Penev V, Krylov SB, Boyadjiev CH, Vorotilin VP. Wavy flow of thin liquid film. Int J Heat Mass Transfer 1968;15:1389–406.
[24] Holmes RE, Chapman AJ. Condensation of Freon-114 in the presence of a strong nounniform alternating electric field. J Heat Transfer Trans ASME 1970:616–20.
[25] Trommelmans J, Janssens J, Maelfat F, Berghmans J. Electric field heat transfer augmentation during condensation of nonconducting fluids on a horizontal surface. IEEE Trans Ind Appl IA-21 1985;2:530–4.
[26] Al-Ahmadi A, Al-Dadah RK. A new set correlation for EHD enhanced condensation heat transfer of tubular systems. Appl Therm Eng 2002;22:1981–2001.
[27] Trommelmans J, Berghmans J. Inuence of electric elds on condensation heat transfer of nonconducting uids on horizontal tubes. In: proceedings of the international heat transfer conference.vol. 6 1986 p. 2969–74.
[28] Bologa MK, Sajin TM, Kozhukhar LA, Klimov SM, Motorin OV. The influence of electric fields on basic processes connected with physical phenomena in two-phase systems. International conference on conduction and breakdown in dielectric liquid 1996:69–72.
[29] Jia-Xiang Y, Li-Jian D, Yang H. An experimental study of EHD coupled heat transfer. IEEE 1996;1:348–51.
[30] Cheung K, Ohadi MM, Dessiatoun SV. EHD-assisted external condensation of R-134a on smooth horizontal and vertical tubes. Int J Heat and Mass Transfer 1999;42:1747–55.
[31] Silva LWD, Molki M, Ohadi MM. Electrohydrodydamic enhancement of R-134a condensation on enhanced tubes. IEEE 2000:757–64.
[32] Butrymowicz D, Marian T, Karwacki J. Enhancement of condensation heat transfer by means of passive and active condensate drainage techniques. Int J Therm Sci 2002;26:473–84.
[33] Yu Z, Hallinan KP, Kashani RA. Temperature control of electrohydrodynamic micro heat pipes. Exp Therm Fluid Sci 2003;27:867–75.

[34] Cotton JS, Brocilo D, Chang JS, Shoukri M, Smith-Pollard T. Numerical simulation of electric field distributions in electrohydrodynamic two-phase flow regimes. IEEE Trans Dielect Elect In 2003;10:37–51.
[35] Cao W, Nishiyama Y, Koide S. Electrohydrodynamic drying characteristics of wheat using high voltage electrostatic field. J Food Eng 2003;62(3):209–13.
[36] Lin CW, Jang JY. 3D numerical micro-cooling analysis for an electrohydrodynamic micro-pump. Sens Actuators A Phys 2005.
[37] Velkoff HR, Miller JH. Condensation of vapor on a vertical plate with a transverse electrostatic field. J Heat Transfer Trans ASME 1965;197–201.
[38] Choi HY, Reynolds M. Study of electrostatic effects on condensing heat transfer. Air force Technical Report AFFDL-TR65-51, Air Force Dynamic Laboratory, Wright-Patterson Air Force Base, Ohio, 1965:124.
[39] Choi HY. Electrohydrodynamic condensation heat transfer. J Heat Transfer. Trans ASME 1968:98–102.
[40] Bologa MK, Didkovesky AB. Enhancement of heat transfer in film condensation of vapour of dielectric fluid by superposition of electric fields. Heat Transfer Soviet Res 1977;9:147–51.
[41] Bologa MK, Savin IK, Didkovsky AB. Electric-field-induced enhancement of vapour condensation heat transfer in the presence of a non-condensable gas. Int J Heat Mass Transfer 1987;30:1577–85.
[42] Bologa MK, Korovkin VP, Savin IK. Mechanism of condensation heat transfer enhancement in an electric field and the role of capillary processes. Int J Heat Mass Transfer 1995;38:175–82.
[43] Sminov GF, Lunev VG. Heat transfer during condensation of vapour of dielectric in electric field. Appl Electric Phenom USSR 1978;2:37–42.
[44] Didkovsky AB, Bologa MK. Vapour film condensation heat transfer and hydrodynamics under the influence of an electric field. Int J Heat Mass Transfer 1981;24:811–9.
[45] Dyakowski T, Trommelmans J, Berghmans J. Theoretical investigation of the effect on an electric field upon vertical plate condensation heat transfer. In: proceeding of the soviet international heat transfer conference. vol. 5 1982 p. 65–70.
[46] Wawzyniak M, Seyed-Yagoobi J. Experimental study of electrohydrodynamically augmented condensation heat transfer on a smooth and an enhanced tube. J Heat Transfer Trans ASME 1996;118:499–502.
[47] Bologa MK, Didkovskiy AB. Enhancement of heat transfer in film condensation of vapours of dielectric liquids by superposition of electric fields. Heat Transfer Soviet Res 1997;9(1):147–51.
[48] Cooper P, Allen PHG. The potential of electrically enhanced condensers Proceedings second international symposium on the large scale application of heat pumps, Oxford, U.K. 1984 p. 295–309.
[49] Damianidis C, Collins MW, Karayiannis TG, Allen PHG. EHD effect in condensation of dielectric fluids Proceeding second international symposium on condensers and condensation, Bath, U.K. 1990 p. 505–18.
[50] Seth AK, Lee L. The effect of an electric field in the presence of noncondensable gas on film condensation heat transfer. J Heat Transfer Trans ASME 1970;9(1):616–62.
[51] Yabe A, Kikuchi K, Taketani T, Mori Y, Hijikata K. Augmentation of condensation heat transfer by applying non-uniform electric field Proceeding seventh international heat transfer conference 1982 p. 189–94.
[52] Yabe A, Taketani T, Kikuchi K, Mori Y, Miki H. Augmentation of condensation heat transfer by applying electro-hydro-dynamical pseudo-dropwise condensation. ibid, 2957–2962.
[53] Ogata J, Yabe A. Augmentation of boiling heat transfer by utilizing the EHD effect -EHD behaviour of boiling bubbles and heat transfer characteristics. Int J Heat Mass Transfer 1993;36:783–91.
[54] Ogata J, Yabe A. Basic study on the enhancement of nucleate boiling heat transfer by applying electric fields. Int J Heat Mass Transfer 1993;36:742–75.
[55] Ogata J, Yabe A. Augmentation of nucleate boiling heat transfer by applying electric fields: EHD behaviour of boiling bubble. Proc ASME/JSME Therm Eng 1991;3:41–6.
[56] Damianidis C, Karayiannis TG, Al-Dadah RK, James RW, Collins MW, Allen PHG. EHD boiling enhancement in shell-and-tube evaporators and its application in refrigeration. ASHRAE Trans 1992;98:462–72.
[57] Allen PHG, Cooper P. The potential of electrically enhanced evaporators Third international symposium on the large scale application of heat pumps, Oxford, UK 1987 p. 221–9.
[58] Jalaluddin AK, Sinha DW. Effect of an electric field on the superheat of liquids. Nuovo Cimento 26 Ser X 1962;234–7.
[59] Karayiannis TG, Allen PHG. Electro-hydrodynamic enhancement of two-phase heat transfer. Eurotech Direct Cong Thermofluid Eng 1991;165–81.
[60] Markels M, Durfee RL. Studies of boiling heat transfer with electric fields. AICHE J 1965;11:716–21.

[61] Markels M, Durfee RL. The effect of applied voltage on boiling heat transfer. AICHE J 1964;10: 106–10.
[62] Budov VM, Kir'yanov BA, Shemagin IA. Heat transfer in the laminar-wave section of condensation of a stationary vapour. J Eng Phys 1987;52:647–8.
[63] Grigor'eva NI, Nakoryakov VE. Exact solution of combined heat and mass transfer during film absorption. J Eng Phys 1977;33:893–8.
[64] Penev V, Krylov SB, Boyadjiev CH, Vorotilin VP. Wavy flow of thin liquid film. Int J Heat Mass Transfer 1968;15:1389–406.
[65] Berghmans J. Electrostatic fields and the maximum heat flux. Int J Heat Mass Transfer 1975; 21:791–9.
[66] Paper RA, Ohadi MM, Kumar A, Ansari AI. Effect of electrode geometry on EHD-enhanced boiling of R-123/oil mixture. ASHRAE Trans 1993;99:1237–43.
[67] Oh SD, Kwak HY. A study of bubble behavior and boiling heat transfer enhancement under electric field. Chung-Ang University, Seoul. J Heat Transfer; Submitted for Publication.
[68] Neve RS, Yan YY. Enhancement of heat exchanger performance using combined electrohydrodynamic and passive methods. Int J Heat Fluid Flow 1996;17:403–9.
[69] Cho HJ, Kang IS, Kweon YC, Kim MH. Study of the behavior of a bubble attached to a wall in a uniform electric field. Int J Multiphase Flow 1996;22:909–22.
[70] Cho HJ, Kang IS, Kweon YC, Kim MH. Numerical study of the behavior of a bubble attached to a nonuniform electric field. Int J Multiphase Flow 1998;24:479–98.
[71] Cheung K, Ohadi MM, Dessiatoun SV, Singh A. EHD-enhanced boiling coefficients and visualization of R-134a over enhanced tubes. Trans ASME 1997;119:332–8.
[72] Verplaetsen F, Berghmans JA. The influence of an electric field on the heat transfer rate during film boiling of stagnant fluids. Rev Gén Therm 1997;37.
[73] Kweon YC, Kim MH, Cho HJ, Kang IS. Study on the deformation and departure of a bubble attached to a wall in D.C./A.C. electric fields. Int J Multiphase Flow 1998;24:145–62.
[74] Kweon YC, Kim MH. Experimental study on nucleate boiling enhancement and bubble dynamic behavior in saturated pool boiling using a nonuniform DC electric field. Int J Multiphase Flow 2000;26:1351–68.
[75] Karayiannis TG. EHD boiling heat transfer enhancement of R123 and R11 on a tube bundle. Appl Therm Eng 1998;18:809–17.
[76] Pascual CC, Stromberger JH, Jeter SM, Abdel-Khalik SI. An empirical correlation for electrohydrodynamic enhancement of natural convection. Int J Heat Mass Transfer 2000;43:1965–74.
[77] Pascual CC, Jeter SM, Abdel-Khalik SI. A statistical analysis of EHD-enhanced nucleate boiling along a heated wire. Int J Heat Mass Transfer 2001;44:1201–12.
[78] Pascual CC, Jeter SM, Abdel-Khalik SI. Visualization of boiling bubble dynamics using a flat uniformly heated transparent surface. Int J Heat Mass Transfer 2002;45:691–6.
[79] Feng Y, Seyed-Yagoobi J. Linear instability analysis of a horizontal 2 phase in the presence of electrohydrodynamic extraction force. J Heat Transfer Trans ASME 2002;124:102–10.
[80] Yamashita K, Yabe A. Electrohydrodynamic enhancement of falling film evaporator heat transfer and its long-term effect on heat exchange. J Heat Transfer 1997;119:339–47.
[81] Liu Y, Li R, Wang F, Yu H. The effect of electrode polarity on EHD enhancement of boiling heat transfer in a vertical tube. Exp Therm Fluid Sci 2004;29:601–8.
[82] Blachowicz RA, Brooks BW, Tan KB. Boiling heat transfer in an electric field. Chem Eng Sci 1980; 35:761–2.
[83] Bochirol L, Bonjour E, Weil L. Exchanges thermiques-Etude de l'action de champs electriques sur les transfers de chaleur dans les liquids bouillants. CR Heb Des Seances de l' Acad Des Sciences (Paris) 1960;250:76–8.
[84] Cooper P. EHD enhancement of nucleate boiling. J Heat Transfer Trans ASME 1990;446–58.
[85] Kawahira H, Kubo Y, Yokoyama T. The effect of an electric field on boiling heat transfer of refrigerant 11. Proc IEEE/IAS Ann Meet 1987;1446–54.
[86] Karayiannis TG, Collins MW, Allen PHG. Electrohydrodynamic enhancement of nucleate boiling heat transfer in heat exchangers. J Chem Eng Commun 1989(81):15–24.
[87] Ohadi MM, Papar RA, Ng TL, Faani MA, Radermacher R. EHD enhancement of shell-side boiling heat transfer coefficients of R-123/oil mixture. ASHRAE Trans 1992;427–34.

[88] Ogata J, Iwafuji Y, Shimada Y, Yamazaki T. Boiling heat transfer enhancement in tube-bundle evaporators utilizing electric field effects. ASHRAE Trans 1992;98:435–44.
[89] Schnurmann R, Lardge MGC. Enhanced heat flux in non-uniform electric fields. Proc R Soc Lond A 1973;334:71–82.
[90] Watson PK. Influence of an electric field upon the heat transfer from a hot wire to an insulating liquid. Nature 1961;189:563–4.
[91] Yabe A, Taketani T, Maki H, Takahashi K, Nakadai Y. Experimental study of electrohydrodynamically (EHD) enhanced evaporator for nonazeotropic mixtures. ASHRAE Trans 1992;98:455–61.
[92] Zheltukin VA, Solomatnikov YK, Mikhaylov DM, Usmanov AG. Effect of electric-field frequency on heat transfer. Heat Transfer Soviet Res 1978;10(6):10–3.